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ONIUM PRODUCTION[♡]

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The present status of our understanding of onium production is reviewed. Different models are described and comparisons of theoretical prediction with experimental data are given.

In this talk I will review the present status of our understanding of onium production. Rather than showing many detailed results I will briefly describe the different production models which are now being considered and tested against experimental data. When describing charmonium photoproduction I will restrict myself to the so-called inelastic domain, since the description of diffractive production would require a talk by itself.

Any model attempting to describe the production of a heavy quarkonium must deal with two issues which can usually be kept distinct: the production of the heavy quark-antiquark pair ($Q\bar{Q}$) constituting the quarkonium and their binding into a single physical long-lived particle.

The details of how these two issues are separated and described will of course depend on the kind of model we consider, but the following general feature can be seen to apply: the production of the heavy quark-antiquark pair is described by all models to take place via a short-distance interaction within perturbative QCD (pQCD). The binding of the two quarks into a bound state is on the other hand a longer distance process, and the models usually invoke non-perturbative effects to take place at this point: this part of the process is usually parametrized via form factors describing the probability of the $Q\bar{Q}$ pair to form the bound state. The degree of rigorousness, completeness and complexity of this part of the description varies greatly from model to model.

Within the last twenty years or so three main models for quarkonia production have been proposed and used to produce theoretical prediction: the Colour Evaporation Model [1] (CEM), the Colour Singlet Model [2] (CSM) and, quite recently, the Factorization Model [3] (FM). They all follow the general "guidelines" outlined above but do however differ in the details of the hadronization description.

The CEM rests on duality arguments in assuming that *any* $Q\bar{Q}$ pair produced with an invariant mass below that of a $D\bar{D}$ mesons pair (i.e. below the

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open charm threshold, using now charm as example of heavy quark) will eventually hadronize into a quarkonium state. While being physically sensible, this model does of course have the big drawback of not being able to predict the production rate of the single quarkonia states. It is therefore not very suitable for the study of exclusive final states.

The CSM tries to overcome the difficulty of the CEM in predicting rates for single states by making a very precise request: the $Q\bar{Q}$ pair must be produced in the short-distance interaction with the spin, angular momentum and colour quantum numbers of the quarkonium. A single phenomenological parameter will then parametrize its hadronization into the observable particle. This model is of course much more predictive: the production rate for a colour-singlet $Q\bar{Q}$ state with a given spin and angular momentum can be calculated exactly in pQCD. Moreover, the phenomenological parameter can be measured, for instance, in electromagnetic decays and used to make absolute prediction about production rates. Still, also the CSM has its own drawbacks, which have eventually led to develop a new model. First of all, the simple minded factorization "cross section for producing quarkonium equals cross section for producing colour-singlet $Q\bar{Q}$ with the proper spin/angular momentum quantum numbers times a phenomenological parameter" is known to fail. Infrared divergences show up in the calculation of the short distance part for P-wave hadronic decays or production[5]: a clear signal that this way of separating short from long distance dynamics is wrong or at least incomplete. Secondly, CSM predictions for producing J/ψ and ψ' states at large p_T have been found to grossly underestimate, by factors of 30 or so, the experimental data obtained by the CDF collaboration [4] in $p\bar{p}$ collisions at the Tevatron (see also [6] and references therein for a review).

The FM (see also ref. [8] for a recent review) has been proposed to overcome the first of these two problems: it extends the CSM by allowing $Q\bar{Q}$ pairs with spin, angular momentum and colour quantum numbers different from those of the observed quarkonium to hadronize into the latter. A general expression for a production cross section within this model then reads

$$d\sigma(H+X) = \sum_n d\hat{\sigma}(Q\bar{Q}(n)+X)\langle\mathcal{O}^H[n]\rangle \qquad (1)$$

Here $d\hat{\sigma}(Q\bar{Q}(n)+X)$ describes the short distance production of a $Q\bar{Q}$ pair in the colour/spin/angular momentum state n, and $\langle\mathcal{O}^H[n]\rangle$, formally a vacuum expectation value of a Non Relativistic QCD matrix element (see [3] for details), describe the hadronization of the pair into an observable quarkonium state H. The cross section is no more given by a single product of a short distance times a long distance part like in the CSM, but rather by a sum of such terms. Infrared singularities which show up in some of the short distance coefficients

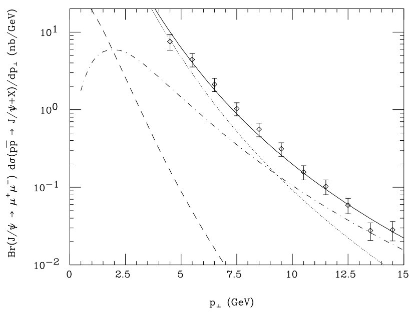

Figure 1: J/ψ production at the Tevatron. Dashed line: Color Singlet Model; dot-dashed line: production via color octet ${}^3S_1$ states; dotted line: production via ${}^1S_0$ and ${}^3P_J$ states. Non perturbative matrix elements for octet states fitted to data. Figure from Cho and Leibovich, ref. [7]

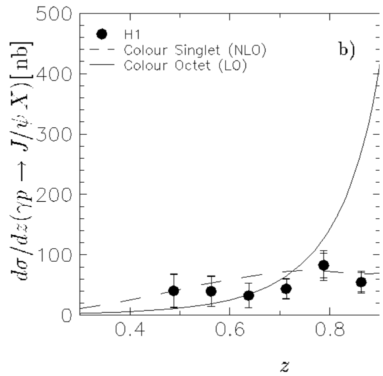

Figure 2: J/ψ production in γp collision at HERA. Dashed line: NLO Color Singlet Model; full line: color octet contributions. Plot from ref.[10]

will be absorbed into the long distance part of other terms, thereby ensuring a finite overall result.

It is obvious that the FM, by extending the CSM, recovers some of the features of the CEM: the state of the $Q\bar{Q}$ pair prepared by the short distance part of the interaction is no more so strongly restricted. This is in agreement with the idea that hadronization is a long-distance/long-time scale process: different quantum states have the time to evolve into a physical quarkonium state after their production in a short distance process, though this evolution is of course suppressed with respect to that of a colour singlet pair with the appropriate quantum numbers [a]. To suppress them completely, like in the CSM, is likely to lead to too small cross sections whenever these states can be copiously produced in the short distance interaction in comparison with the colour singlet ones. This is the case for large p_T J/ψ and ψ' production at the Tevatron: it was found [7] that gluons production and their subsequent fragmentation into a colour octet ${}^3S_1$ $c\bar{c}$ pair (which will eventually hadronize into a physical quarkonium) can successfully describe the experimental data, previously greatly underestimated by the CSM (see fig. 1).

The success of the Factorization Model in the description of quarkonium production at the Tevatron must of course be challenged by comparing its predictions to experimental data from other reactions, like e^+e^- or γp collisions. It turns out that using the non-perturbative matrix elements fitted to the Tevatron data we can produce a parameter free prediction for inelastic

[a] Non Relativistic QCD actually allows one to put these relative suppressions on a more quantitative ground. See ref. [3] for details.

J/ψ photoproduction which can be compared with experimental data obtained at HERA. The result of this calculation [9] is shown in fig. 2, where the experimental data from the H1 Collaboration [10] are also compared to the NLO CSM prediction [11]. The plot shows that the color octet contribution overshoots the data in the large-z region, while the next-to-leading order CSM prediction seems to describe them well. Taken at its face value this result would point to a non-universality of the non-perturbative matrix elements fitted to the Tevatron data and hence to a failure of the FM. On the other hand, many uncertainties can affect the theoretical predictions both for the Tevatron and HERA: higher orders and higher twists could significantly change this picture, and a detailed evaluation of their relevance is so far not available. More work is therefore needed before we can safely handle a successful model for quarkonia production.

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